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Optimal scheduling of distributed battery storage for enhancing the security and the economics of electric power systems with emission constraints

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ABSTRACT

In this paper, the sustainable day-ahead scheduling of electric power systems with the integration of distributed energy storage devices is investigated. The main objective is to minimize the hourly power system operation cost with a cleaner, socially responsible, and sustainable generation of electricity. Emission constraints are enforced to reduce the carbon footprint of conventional thermal generating units. The stationary electric vehicles (EV) are considered as an example of distributed storage and vehicle to grid (V2G) technology is considered to demonstrate the bilateral role of EV as supplier and consumer of energy. Battery storage can ease the impact of variability of renewable energy sources on power system operations and reduce the impact of thermal generation emission at peak hours. We model the day-ahead scheduling of electric power systems as a mixed-integer linear programing (MILP) problem for solving the hourly security-constraint unit commitment (SCUC). In order to expedite the real-time solution for large-scale power systems, we consider a two-stage model of the hourly SCUC by applying the Benders decomposition (BD). The Benders decomposition would separate the hourly generation unit commitment (UC) in the master problem from the power network security check in subproblem. The subproblem would check dc network security constraints for the given UC solution to determine whether a converged and secure dc power flow can be obtained. If any power network violations arise, corresponding Benders cuts are formed and added to the master problem for solving the next iteration of UC. The iterative process will continue until the network violations are eliminated and a converged hourly solution is found for scheduling the power generating units. Numerical simulations are presented to illustrate the effectiveness of the proposed MILP approach and its potentials as an optimization tool for sustainable operations of electric power grids.

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1. Introduction

Sustainability refers to a balance of social and economic activities in a cleaner environment. Addressing resource scarcity for an unbiased sustainable economic development is one of the greatest priorities in our era. The planning philosophy for the existing electricity grid is a transformation from an era when energy was inexpensive and abundant while addressing the rising demand was the primary concern. We are at evolution to a period when clean energy is at premium, power systems require an adaption to low greenhouse gas (GHG) emission technologies for electricity supply, and customers request greater awareness and participation in energy utilization. Moreover, operating at absolute minimum cost is no longer the only condition for electric power generation due to the pressing public demand for cleaner air [1].

The electric power industry around the globe has experienced an era of rapid and critical changes concerning the way electricity is generated, transmitted, and distributed since the mid-1980s. The necessity for more efficiency in power production and delivery, traditionally under the control of federal and state governments, has resulted in privatization, restructuring, and ultimately deregulation of power sectors in several countries including the United States.

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Nomenclature

Variables

b, j, o	index of bus
$C_{v,(\cdot)}$	operation cost of the EV fleet v
e	index for emission
$E_{v,t}^{(\cdot)}$	available energy in batteries of fleet v at time t
$E_{v,t}^{net}$	net discharged energy of EV fleet v at time t
$F_{c,(\cdot)}$	production cost function of a thermal unit
$F_{e,i}(\cdot)$	emission function of unit i
i	index of thermal units
I_{it}	commitment state of unit i at time t
$I_{c,(\cdot)}^{(\cdot)}$	indicator of EV fleet in charging mode
$I_{dc,(\cdot)}^{(\cdot)}$	indicator of EV fleet in discharging mode
l	index of transmission line (l = 1 to 7)
$P_{i,t}$	generation of a unit i at time t
$PL_{l,t}^{(\cdot)}$	real power flow on line L at hour t
$P_{c,(\cdot)}^{(\cdot)}, P_{dc,(\cdot)}^{(\cdot)}$	charge/discharge power of EV fleet
$P_{m,(\cdot)}^{(\cdot)}$	charge/discharge power rate at segment m
$SD_{e,it}$	shutdown emission of unit i at time t
$SU_{e,it}$	startup emission of unit i at time t
$SD_{(\cdot)}^{(\cdot)}$	shutdown cost of a unit
$SU_{(\cdot)}^{(\cdot)}$	startup cost of a unit
t	hour index (t = 1 to 24)
v	represents an EV fleet
X_{off}^{it}	OFF time of unit i at time t
X_{on}^{it}	ON time of unit i at time t
$\theta_{(\cdot)}^{(\cdot)}$	voltage bus angle

Parameters

$B_{b,t}^{(\cdot)}$	set of units that are connected to bus b at time t
$b_{m,v}$	slope of segment m in linearized charge/discharge curve for EV fleet v
D_b	set of loads that are connected to bus b
DR_i	ramp-down rate of unit i
$E_v^{\min}, E_v^{\max}$	min/max energy stored in batteries of EV fleet v
$E_{v,0}, E_{v,NT}$	initial and terminal stored energy in EV fleet v
$EMS_{\max}^{ET}$	maximum allowable emission for the operation period for emission type ET
$L_{f,b}, L_{t,b}$	set of lines starting from/ending at bus b
$N_{v,t}$	status of grid connection of fleet v at time t
NG	number of units
NL	number of lines
NB	number of buses
NT	number of periods under study (24 h)
$P_{c,v}^{\min}, P_{c,v}^{\max}$	min/max charging capacity of EV fleet v
$P_{D,t}$	system demand at time t
$P_{dc,v}^{\min}, P_{dc,v}^{\max}$	min/max discharging capacity of EV fleet v
$P_{m,v}^{\max}$:	maximum power output at segment m in charging/discharging cost curve of EV fleet v
$P_{i,\min}$	lower limit of real power generation of unit i
$P_{i,\max}$	upper limit of real power generation of unit i
$PL_l^{\max}$	maximum capacity of line l
T_{off}^i	min down time of unit i
T_{on}^i	min up time of unit i
UR_i	ramp-up rate of unit i
X_{jo}	inductance of a line between buses j and o
η_v	cycle charging efficiency of EV fleet

Because of extreme variations between peak and off peak hours in the generation scheduling horizon, expensive generating units which are generally scheduled for providing peak loads should be shut down at off-peak hours to minimize the constrained economic dispatch of generating units. Economic dispatch (ED) and unit commitment are two basic concepts in the economic operation of electric power systems. ED would determine the least cost operation of a power system by dispatching the available electricity generation resources to supply the hourly system load, while satisfying the operation constraints of available generation resources. Short-term UC will outline the hourly ON/OFF status of thermal units over a day while contemplating the cost and addressing physical constraints for starting-up and shutting down of thermal units [2].

Producing and maintaining enough power to serve peak loads on top of the urge for developing a low-carbon economy require significant evolutions in the electricity grid infrastructure. One way to accelerate this transformation is to store energy when demand is less and put that energy back on the grid when demand spikes. The problem is that the battery technology is not where we need it to be in terms of energy density and cost as such utilities cannot afford to buy large and central batteries in order to implement the battery storage scenario. That is where the distributed storage in EVs can come in and play a constructive role. Furthermore, replacing internal combustion engine cars with more EVs on the road can significantly lower CO_2 levels. According to the IEA's World Energy Outlook 2011 [3], "For every $1 of investment avoided in the power sector before 2020, an additional $4.30 would need to be spent after 2020 to compensate for increased GHG emissions."

The integration of aggregated fleets of EVs into the electricity grid as distributed resources is known as V2G. To sustain economic growth, V2G provides a migration path toward energy independence. Establishing new and efficient power systems that integrate conventional and renewable sources, supported by V2G, can convey higher energy efficiency, reduce expected grid operation costs, and lower GHG emissions.

Moreover, the presence of variable generation assets (such as wind and solar) in the electricity grid has introduced major reliability challenges for power grid operators. In the case of wind, supply is often negatively correlated with the hourly load since wind power generation is frequently high at night when the hourly demand is low. Deployment of EVs as virtual power plants would allow greater use of renewable energy in electricity generation as batteries can replenish energy corresponding to hourly load requirements [4].

The emergence of smart grid has initiated a new revolution in the power sector. Smart grid is an electricity transmission and distribution network that has the capability to quickly integrate, simplify and understand large amounts of information and utilize it properly by making intensive use of both, automation and information and communication technologies (ICTs). Smart grid has profoundly changed the way electricity is produced, consumed and distributed. Smart grid's novel network structure allows for efficient use of distributed energy resources (DERs) including distributed generation, renewable energy sources and distributed energy storage. Smart grid applies a cluster of loads using energy demand response (DR) for offering significant control capacities in power system operations. By merging smart grid technology with aggregated EV fleets as distributed battery storage facilities, we will have an opportunity to provide ample resources for peak load reductions. EV fleets as distributed battery storage devices can facilitate the balance of supply and demand which could otherwise make it difficult to stabilize the system frequency [5].

Several studies have explored both the potential promise and the possible pitfalls of EV integration into the power system grid. The 2012 report in [6], "Bucks for Balancing", evaluates the potential for plug-in vehicle as a new source of balancing services to smooth the daily demand profile. The findings indicate that the

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